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Signals in the Soil: An Introduction to Wireless Underground Communications

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Chapter 1
Signals in the Soil: An Introduction to Wireless Underground Communications

Abstract In this chapter, wireless underground (ug) communications are introduced. A detailed overview of WUC is given. A comprehensive review of research challenges in WUC is presented. The evolution of underground wireless is also discussed. Moreover, different component of the of UG communications are Wireless. The WUC system architecture is explained with a detailed discussion of the anatomy of an underground mote. The examples of ug wireless communication systems are explored. Furthermore, the differences of UG Wireless and Over-the-Air Wireless are debated. Different types of wireless underground Channel (e.g., In-Soil, Soil-to-Air, and Air-to-Soil) are reported as well.

1.1 Introduction

Wireless Underground Communication (WUC) is becoming popular because of it's secured deployment methodology, i.e., concealed far below the ground. Underground communication was first observed in World War, however, its use was limited to radio propagation techniques only. V. Fritsch and R. Wundt conducted the experiments, in 1938-1940, to study the propagation of radio waves in underground coal mines using small transceivers deployed below the ground. Although, the communication range varied depending upon the nature of the coal, however, they were successfully able to achieve an overall range of upto 1000 feet. In 1942, they conducted another experiment at the depth of 2000 feet, however, the experiments were conducted in 100 feet thick salt mine instead of coal mine. For the salt mine experiment, a battery operated horizontal dipole antenna was used as transmitter and receiver. They performed voice communication using the amplitude modulation. The experiment was performed with extreme care and intelligence to avoid extraneous noise or any other added radio signals at transmitter. It was made sure that no measurable wave existed on the earth surface so that true underground propagation can be studied. Moreover, transmitter and receiver were separated by a carefully planned distance. A range of 15 km, i.e., 9-1/2 miles, was successfully achieved for voice communication.

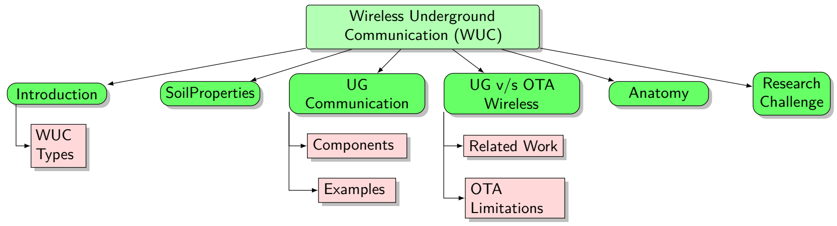

Fig. 1.1: Organization of the Chapter

Since then, underground communication has come long way with improvement in methodologies and equipment. This Chapter discusses the potential and challenges of underground communication.

Smart Farming [9, 50, 52, 56, 58, 62, 72, 75, 100, 104, 145, 155] is an agricultural management process which exploits the spatio-temporal changes in crop, soil, management and production with new technologies to improve the farming experience. Smart farming employs large number of wireless devices to sense crop-related data and send this data to a central control room or server center [32, 71]. In recent years, sensing technologies have evolved a lot. These advanced sensing methods are then combined with adaptive input applications (e.g., adaptive application of fertilizers) and soil mapping methods for efficient operation.

In recent years, evolution and advancement in sensing technologies have risen the demand of high data rates and increased communication range. As per the reports of Cisco's visual networking index [1], 11.6 billion devices are predicted to be connected via Internet by 2020. The vastness of this number can be realized by the fact that population of the world is predicted to be 10 billion by 2050, i.e., even less than the predicted number of connected devices by 2020. To fulfill food requirement of such a huge population of the world, it is imperative to utilize smart farming methodologies for a better and cost-efficient crop production through timely decision making and conserving natural resources. To that end, it is important to achieve an ubiquitous connectivity on the farms by using underground wireless communications channel [53, 71, 72].

Wireless Underground Communications (WUC) applications can be classified into various categories [28, 38, 46]. Some of them, for example, includes: environment monitoring, e.g., precision agriculture and landslide monitoring, infrastructure monitoring, e.g., preventing leakage and urban infrastructure monitoring, application for determining location can be helpful in locating people stuck in disaster, and security monitoring applications, e.g., to detect infiltration at border through concealed underground devices. Fig. 1.2 shows some of these applications [27].

WUC and conventional wireless networks differs mainly in the communication medium they use. WUC sensor nodes communicate through soil where as over-the-air (OTA) terrestrial wireless network uses air as a medium to communicate. The signal propagation in soil is never investigated properly before, in fact, electromagnetic (EM) wave propagation was not even considered a viable option for underground (UG)

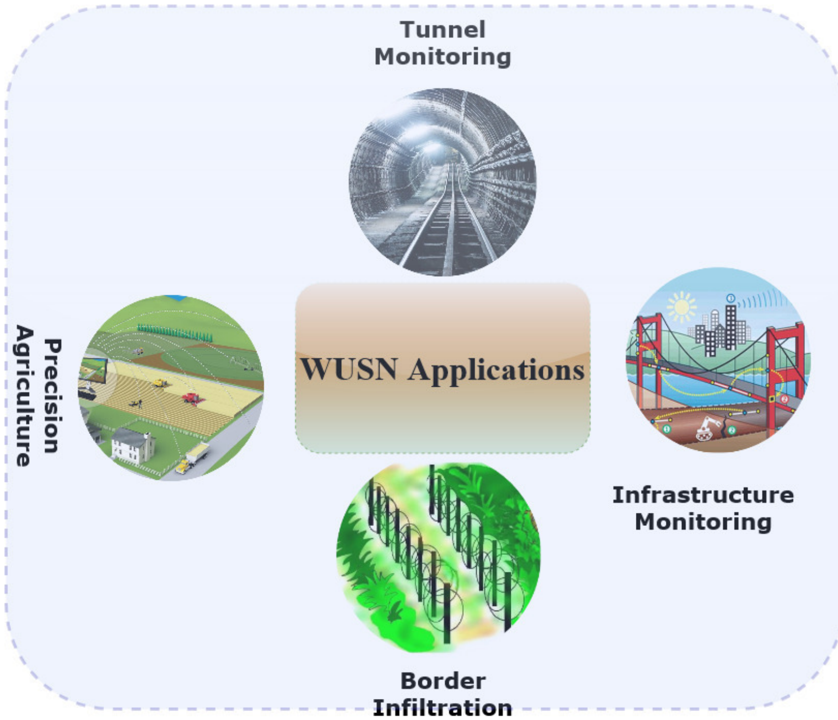

Fig. 1.2: Use of Wireless Underground Communications (WUC) in different areas

communication. Therefore, feasible options and solutions are explored to develop a power-efficient UG communications.

There is a lack of detailed wireless channel model because of the challenges experienced in developing a power-efficient UG communication system which also hinders the protocol development in WUC. To that end, existing literature was studied in detail along with a very detailed and time-intensive experiments [57, 59, 60, 70, 206]. The results from these experiments were analyzed over a period of 18 months to generalize performance of an UG communication channel. A summary of those results can be found in [210]. It was observed that many soil parameters (e.g., soil texture and moisture and irregular soil surface), and antenna parameters (burial depth, antenna design, and operating frequency) has effect on UG communication. It substantiate the fact that performance of an underground channel can highly be effected by the spatio-temporal environmental factors leading to a unique correlation of communication systems, i.e., both information data and communication medium, with environment. Hence, in addition to operational and deployment factors, these parameters should also not be overlooked while analyzing an underground channel.

A wireless underground communications (WUC) model has been developed and presented in [210]. The model focuses on propagation model rather than antenna problem. This WUC model determines the total signal attenuation and the BER

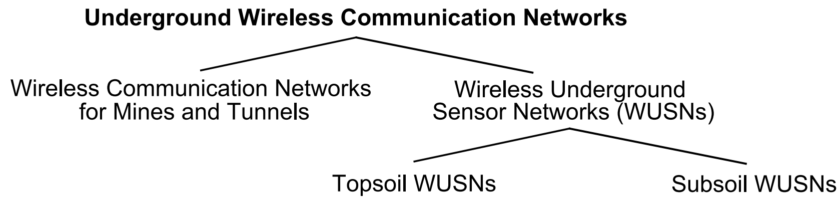

Fig. 1.3: The different types of networking in (WUC) [260]

(bit error rate) using three-wave components (direct wave (DW), reflected wave (RW), and lateral wave (LW)), dielectric soil properties prediction model, and the signal superposition model. In contrast to existing literature, WUC model captures the gain from the directivity of special antennas instead of simple insulated dipole [51, 52]. However, to avoid over-complication of the model, antennas problem are not considered in this model because of a large number of antennas schemes.

[210] conducted in-situ experiments without considering lateral wave component. However, if lateral waves are also considered along with special antennas, communication range can be increased with same transmitting power. The results obtained from the study helped in designing WUC systems. A strong multi-hop networking solution among the buried nodes can be achieved with long range (distance > $10\,\mathrm{m}$) eliminating the topology dependency of above-ground devices.

In [210], authors have also shown that depth has high effect on communication performance. Through empirical evaluations, they observed that even a small change in depth can degrade the communication performance. The difference in communication performance between topsoil and subsoil is because of:

- **Soil parameters**. Both, topsoil, and subsoil, have different soil texture and soil moisture levels [15] which is the reason for the difference in communication in both mediums [1, 1, 59]. For example, topsoil will have more soil moisture level as compared to subsoil during rain or irrigation because it takes time for water to reach subsoil area [66].
- **Soil surface effects**. LW and RW component plays an important role in high signal strength in topsoil region. Therefore, signal propagating through topsoil experiences much less attenuation as compared to the subsoil region.

It is preferred to have a shallow deployment of UG nodes in WUC because of shorter propagation path in the soil causing signal to suffer less attenuation. However, the depth is highly application-dependent, e.g., for intruder detection, recommended deployment depth is $10\,\mathrm{cm}$ and sport field irrigation, however, for precision agriculture depth of $40\,\mathrm{cm}$ - $100\,\mathrm{cm}$ is mostly recommended.

Another method of underground communication, not given in Fig.1.3, is Through-The-Earth (TTE). TTE is applied in areas like military UG communication, geophysical exploration, and mining. It is mainly used to communicate in emergency

Table 1.1: Typical aspects for Through-The-Earth (TTE) and WUC scenarios [210].

Aspect	**TTE-based communication**	**WUSN**
Frequency range	VLF / LF	VHF / UHF
Maximum range (soil path)	Up to hundred meters	$5\,\mathrm{cm}$ to dozen meters
Bandwidth	Very small: bps	Small: Kbps
Network topology	One-hop	One-hop and multi-hop
Network density	Sender-receiver or few nodes	Hundred to thousand nodes
Underground channel noise	Very critical aspect	Small impact
Rock penetration	Feasible	Usually not feasible
Soil moisture	Small impact	Very critical aspect
Energy criticality	Relatively small impact	Very critical aspect
Node cost	Relatively high	Small
Communication protocol design	Emphasis on the physical layer	Cross-layer approach

situations where people stuck in disasters, e.g., miners stuck in mines[22]. WUC & TTE, with all their similarities, faces completely different set of challenges (see Table 1.1). For example, a typical depth considered for TTE deployment is very deep (hundreds of meters) as compared to WUC (few centimeters). Therefore, they are considered two different technologies in the literature [20, 48, 50].

It can be seen in the Table 1.1 that most of the challenges are related to the physical layer. TTE struggles in traversing rocks with long-range communication, and WUSN struggles in long-range communication through soil. Soil moisture highly effect the subsoil communication [1, 59, 60], therefore, it requires cross-layer approach [1]. Moreover, WUC needs power-efficient nodes buried for long lasting operations.

Relative permittivity of a soil depends upon the signal frequency and Volumetric Water Content (VWC), therefore, signal frequency indirectly effect the strength of the signal [4, 8]. In addition to the frequency, soil conductivity also has an effect on signal attenuation. This is contrary to the popular belief that signal is less attenuated under smaller frequencies. Hence, signal attenuation cannot be estimated from soil permittivity only, other soil parameters also contributes to the attenuation [4, 28].

Soil permittivity estimation has been investigated for a specific range of frequencies. All such studies concludes that frequencies around $1\,\mathrm{GHz}$ produce reasonable soil permittivity values and are suitable for practical wireless systems under $300\,\mathrm{MHz}$ frequencies. However, as the frequency decreases, wavelength of the signal is increased, consequently, increasing the antenna size. Hence, very low frequencies, e.g., less than $300\,\mathrm{MHz}$, are not feasible for WUC. In military WUC, the major requirement is to get longer communication range, e.g., less than $10\,\mathrm{km}$. To that end, military WUC uses HF to LF frequency band filter with huge antennas consuming more power. It is shown that the signal suffers with much less attenuation under UHF bands ($300\,\mathrm{MHz}$ - $3\,\mathrm{GHz}$), and frequencies ranging from $300\,\mathrm{MHz}$ - $1\,\mathrm{GHz}$ [59] which makes them optimal to be used in practical WUC [32, 54].

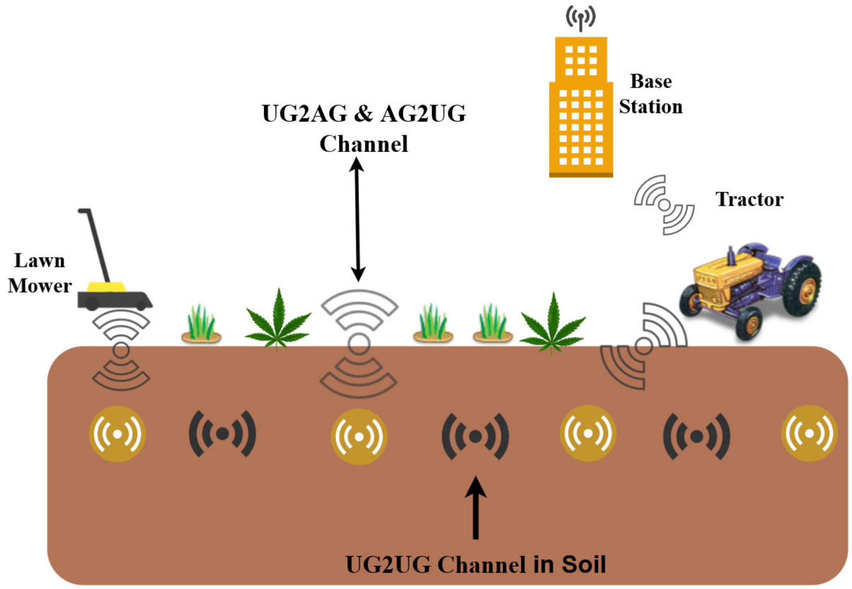

Fig. 1.4: Hybrid WUC Architecture

1.2 Types of Wireless Underground Channel

WUC does not contain only UG nodes. Hybrid WUC is a combination of underground (UG) and aboveground (AG) nodes [1, 47, 49]. As Hybrid WUC contains multiple types of devices, it also utilize multiple type of links for communication between them, i.e., aboveground-to-underground (AG2UG), underground-to-underground (UG2UG), and underground-to-aboveground (UG2AG). Fig. 1.4 shows one such hybrid WUC in an agricultural setup where various UG sensors nodes are communicating with each other from soil medium, through UG2UG channel, with different AG nodes and vice versa. AG nodes, i.e., agricultural equipment and Base Station, sends data to UG nodes through through AG2UG channel. Similarly, UG nodes sends data to AG nodes through UG2AG channel. Here, this book focuses on the characterization of WUC UG2UG channel. Moreover, other WUC channels, i.e., AG2UG & UG2AG channels, can be characterized using WUC channel model.

Lateral waves have been extensively used in UG communications [23, 25, 27, 33] and empirically evaluated by [23, 77, 257]. Special antennas (eccentrically insulated traveling-wave (EITW) antenna) are used for empirical evaluation. Underground lateral wave communication is empirically evaluated through following UG2AG experiment setup: burial depth is $40\,\mathrm{cm}$, aboveground antenna and soil surface were separated by the distance of 55cm, transmit power level is maintained at $30\,\mathrm{dBm}$, and frequency of $144\,\mathrm{MHz}$ is used. The study [23] was successful to achieve longer communication range of $50\,\mathrm{m}$ [44].

In [30, 46, 224], authors performed experiment to empirically evaluate UG2AG communication. The experiment setup for this study is given as follow: Terrestrial commodity sensors MicaZ [3] motes were used as UG node, operational frequency of $2.4\,\mathrm{GHz}$, burial depths of $0\,\mathrm{cm}$, $6\,\mathrm{cm}$, and $13\,\mathrm{cm}$, and transmit power level of $0\,\mathrm{dBm}$ was used. The experiments were performed in two sets of sender-receiver scenario. Both sets differed in distance between soil and receiver. For the first set, the receiver was kept on the soil (distance = $0\,\mathrm{m}$) and the second set was performed with a distance of $1\,\mathrm{m}$ between soil and the receiver. The UG2AG communication was evaluated for two metrics: packet error rate (PER) and received signal strength (RSS). First experiment, with a distance of $0\,\mathrm{m}$, was used as baseline experiment to compare it with the second experiment. It was observed that node buried at $13\,\mathrm{m}$ depth was able to communicate at maximum horizontal distance of $2.5\,\mathrm{m}$ and node at $6\,\mathrm{cm}$ depth achieved a maximum of $7\,\mathrm{m}$ horizontal communication range. Hence, it shows that attenuation is inversely proportional to the path covered by the signal in the soil. The study achieved the PER of $10\,\%$ [29, 33, 65].

In [5, 26, 35], a uni-directional UG2AG communication model was studied with an effect of reflection dielectric on the signal attenuation. The model is validated through laboratory experiments. The experiment setup was as follow: SoilNet was used as sensors node, operational frequency was $2.44\,\mathrm{GHz}$, transmit power of $19\,\mathrm{dBm}$ was used, and sensor were buried at different depth ranging from $5\,\mathrm{cm}$ to $9\,\mathrm{cm}$. The strength of the received signal was measured by a soil probe. It was observed that for soil width of $1\,\mathrm{cm}$ to $7\,\mathrm{cm}$, signal attenuation was increased up to $25\,\mathrm{dB}$. However, $10\,\mathrm{dBm}$ of attenuation was observed with $0\,\%$ to $35\,\%$ increase in VWC of the soil [36, 53]. Moreover, bulk density and bulk electrical conductivity had a negligible effect on signal attenuation. The results confirms the empirical results presented by [210].

[28, 68] proposed a UG2AG communication model using a customized sensor node: *Soil Scout*. Following parameters were used for the experiments: operation frequency of $869\,\mathrm{MHz}$, transmit power of $+10\,\mathrm{dBm}$, and an ultra wideband elliptical antenna [36, 41, 146] was used for underground communication [74] and model validation. The model predicts signal attenuation on the basis of (a) reflection effects of a soil surface, (b) dielectric loss of the soil, and (c) refraction effect of an EM waves at soil surface (angular defocusing). It was shown that wideband antenna radiation pattern is independent of soil texture and soil moisture and showed efficient radiation in different soil types with varying soil moisture levels. The study [33, 40, 68] was successful to achieve long communication range of $30\,\mathrm{m}$ and $150\,\mathrm{m}$ at the burial depths of $40\,\mathrm{cm}$ and $25\,\mathrm{cm}$, respectively.

In [34, 37, 42], experiments are performed using customized sensor nodes. The experimental setup was as follow: burial depth was 10cm, operational frequency of $869\,\mathrm{MHz}$ is used, and transmit signal power was $+10\,\mathrm{dBm}$. [60] performs experiments for evaluating AG2UG and UG2AG communication links. It uses Mica2 motes as sensor nodes, operational frequency and transmitting power are $433\,\mathrm{MHz}$ and $+10\,\mathrm{dBm}$, respectively. Moreover, they used an ultra-wide band antenna [146] which resulted in significantly improved communication range of $22\,\mathrm{m}$ and $37\,\mathrm{m}$ at the depths of $35\,\mathrm{cm}$ and $15\,\mathrm{cm}$, respectively. Similarly, [70] performs AG2UG and UG2AG experiments with Mica2 motes for precision irrigation application [34, 43].

Although UG2UG communication has been investigated a lot in the existing literature, however, there is still a gap in literature for detailed UG2UG communication channel characterization in subsurface soil region. Only few studies [1, 38, 39, 59] have performed theoretical and empirical analyses of UG2UG communication link. Therefore, a detailed characterization of UG2UG communication channel is presented in the coming sections.

1.3 Underground Communications Overview

Most commercially available solutions uses over-the-air (OTA) communication solutions. One of the major challenge in implementing OTA solutions is their unknown environmental impact. WUC uses soil as a medium for wireless underground communications. There are many license-free solutions (e.g., ZigBee, Bluetooth and DASH7) available for short-range communication. These are used in Industrial, Scientific and Medical (ISM) bands. Recently, FCC has loosened the restriction on using the TV white space frequencies for farms [2] (Order No. DA 16- 307 Dated: Mar 24, 2016). Interference with other licensed band is not expected in this space.

1.3.1 Components of UG Communications

In UG communications, UG nodes are completely concealed. It reduces the operational cost and external impact from the environmental and weather changes [9]. UG nodes can communicate in any one of the two scenarios: 1) communication with devices above the ground termed as aboveground (AG) communication, 2) communication between the UG nodes is termed as underground (UG) communication. Furthermore, soil-air interface effect the AG communication links. Due to interface, these links are not symmetric and must be analyzed for signals propagating in both directions, i.e., UG-to-AG and AG-to-UG. It shows that in order to achieve multi-hop connectivity, a practical distance for UG communication is limited to $12\,\mathrm{m}$. For AG communication, a communication range up to $200\,\mathrm{m}$ is possible. If the UG communication medium is soil, it can have effect the communication in following ways:

- **Changes in Soil Bulk Density and Soil Texture:** EM waves attenuates in the soil. Soil is composed of various components such as pore spaces, clay, soil and silt particles. There can be 12 soil textures depending upon relative concentration of these components [25]. Bound water is the major component responsible for EM waves attenuation in the soil. The amount of bound water varies from one soil type to other. For example, sandy soil has less bound water from silt loam and silty loam, hence, it suffers from lower attenuation. Similarly, medium textured soils holds more water than coarse soils because of lower pore size.

- **Volumetric Water Content (VWC) of Soil:** The effective permittivity of a soil is a complex number. Therefore, in addition to diffusion attenuation, EM waves suffers attenuation due to absorption of water content by the soil [61], [9], [157]. Dielectric spectra conductivity of the soil is dependent on VWC or soil moisture. For a dry soil, dielectric constant is in the range of 2 and 6 and conductivity is in the range of $10^{-4}\,\mathrm{S/m}$ to $10^{-5}\,\mathrm{S/m}$. For a near-saturation level soil, range of dielectric constant is 5 to 15 and that of conductivity is in the $10^{-4}\,\mathrm{S/m}$ to $10^{-5}\,\mathrm{S/m}$ [68]. Coherence bandwidth of UG channel is a few hundred kHz [47, 63, 64]. Coherence bandwidth changes with the change in SM which makes the designing process more challenging.
- **Distance and Depth Variations:** EM waves attenuation also depends upon travel distance of the signals. WUC sensors are normally buried in the top sub-meter layer. Therefore, received strength of the signal varies with the distance and depth of antennas. In WUC, sensors are buried in both, subsoil and topsoil layers [70, 158]. Burial at higher depth results in higher attenuation [47].
- **Antenna in Soil:** Return loss of a buried antenna varies due to high permittivity of soil [62]. Change in soil moisture levels changes soil permittivity which in turn causes variations in return loss. Resonant frequency is shifted to lower frequency spectrum due to change in return loss. Moreover, achieving high overall system bandwidth also becomes challenging for UG communications.
- **Change in Frequency:** The path loss due to attenuation is frequency dependent [7]. High frequencies suffers high attenuation because of increased water absorption. The EM waves in soil have shorter wavelength as compared to EM waves in the air because of higher permittivity of the soil. Channel capacity in soil is also determined by operation frequency [62].
- **Lateral Waves:** Underground nodes communicate with each other using any one of the three major paths: direct, lateral and reflected (LDR) waves [19, 63, 64, 147]. Direct and reflected waves are most effected by above-mentioned challenges because their complete travel path is through the soil. On contrary, lateral waves can travel along soil-air interface in air, hence, they experience lowest attenuation among all. Therefore, lateral waves are the most important component to consider while extending the UG communication range.
- **Developments in WUC:** UG communications have evolved a lot since its inception. A lot of work has been done in characterization of UG channel and cross-layer communication solutions are proposed to get long communication range and achieve high data rate. In [147], authors capture and analyze impulse response of UG channel through detailed experimentation.

A total of 1500 UG green-house testbeds has been developed to analyze the effect of soil moisture and soil texture on wireless UG communication channel. These experiments helped in developing main characteristic of wireless UG channel impulse response such as: root mean square delay spread, coherence bandwidth, and power of multi-path components. It also validates main components of UG channel, i.e., direct, lateral and reflected waves. The coherence bandwidth decreases with the increase in distance in soil, e.g., it is shown in [147] that a coherence bandwidth of less than $1.15\,\mathrm{MHz}$ can decrease further upto $418\,\mathrm{kHz}$, if distance is increased for more than

12 m in soil [147]. Root mean square delay spread is affected by the soil moisture and it should adapt to change in soil moisture values. In [62], an important statistical model for UG multi-carrier communication and soil moisture adaptive beamforming is given for WUC solutions.

1.3.2 Examples of UG Wireless Communication Systems

WUC is being used in many applications: border patrol, precision agriculture, and environment monitoring. WUC mainly consist of two components: sensors and communication devices. These components are either completely or partially buried in the soil. WUC aims to provide real-time soil monitoring and sensing. In precision agriculture, WUC is mainly used for sensing and monitoring of soil and other related physical properties [9, 52, 58, 67, 75, 77, 81, 86, 100, 104, 139, 141, 145, 164]. The WUC are also being used to implement border monitoring for stop border infiltration [54, 71]. Other monitoring applications of WUC includes pipeline monitoring and landslide monitoring [70, 75, 164].

Another important component of WUC is the wireless communication. There exist few models in the literature which represents underground communication. Underwater communication [6, 145] has same challenging medium as of underground communication. However, for underwater communication, acoustic waves [6] are used instead of EM waves due to very high attenuation of EM waves in the water. Acoustic propagation has its own disadvantages such as: low quality of physical link and higher delays because of low speed of sound, extremely low bandwidth, challenging deployment and size and cost of equipment. These disadvantages restrict the use of acoustic methods for WUC.

1.4 Why UG Wireless is different from Over-the-Air Wireless?

Wireless underground communications with magnetic induction (MI) has also been studied in [69, 94, 100, 108, 168, 233]. However, signal strength of MI-based solutions attenuates with the inverse cube factor and suffers from very low data rates. MI communication is also dependent on relative position of receiver and sender as it cannot communicate if both receiver and sender are perpendicular to each other. Furthermore, long wavelength of the magnetic channel does not allow network to scale. These disadvantages and inability of communicating with the aboveground devices does not make MI solutions a feasible option for WUC.

Some literature [61, 177] has given UG channel models without empirical validation. Integration of WUC with precision agriculture cyber-physical systems and center-pivot systems is given in [9]. Underground channel is empirically evaluated in [157, 158], however, they did not consider the antenna bandwidth for evaluation. A 2-wave path loss model is developed in [177], without considering the lateral

Table 1.2: Summary on WUC systems

WUC Systems		
Technology Specific	MI-Based	[100] [94][108][69] [233] [168] [166] [92] [236] [95] [99] [96] [110] [96] [60] [252]
	EM-Based	[265] [218] [114, 115] [69] [281] [201] [44] [70] [77] [276] [8] [56, 276] [81] [58, 74, 277] [102] [279] [62] [64] [45] [226] [55] [31]
	Acoustic Based	[103] [6] [73] [130] [203] [88] [84] [63] [268] [7] [140] [51] [163], [256], [225] [14] [116] [216, 275]
	Channel Modeling	[211] [118] [117] [274] [229] [169] [228]
	Wired	[155] [80] [55] [124] [21] [104] [86] [280] [282] [147]
Application Specific	Agriculture	[265] [281] [44] [58, 74, 277] [103] [203] [51] [216, 275] [279] [283] [66] [28] [62] [64] [45] [147]
	Drilling and Telemetry	[78] [64] [149] [82] [68] [152] [79] [116] [116] [14] [140] [7] [268] [63] [130] [73]
	Oil & Gas	[282] [280] [155] [156] [97] [112] [68] [101] [8] [201]
	Irrigation	[19] [132] [22] [283] [138] [137] [123] [129]
	Mining, Monitoring and Tracking	[86] [104] [21] [155] [121] [122] [120] [4] [75, 76] [5] [98] [163], [256], [88] [225] [44] [284] [127] [151] [125] [240]

wave component. Path loss prediction model has been proposed in [30], however, they did not considered underground communication. In [164], authors presents an underground communication model for mines and road tunnels. However, it cannot be applied to WUC due to difference in wave propagation mechanism in tunnel and soil. A model is proposed by [61] for closed-form path loss with lateral waves but this simple model cannot capture statistics and impulse response of the channel. [145] presents the detailed characteristics of coherence bandwidth of the underground channel.

There is no detailed discussion about the channel capacity in the literature. Capacity of single-carrier underground communication channel has been discussed in [62]. This discussion, however, does not consider a practical modulation scheme and does not perform the empirical validation. In [139], the authors analyze the capacity of multi-carrier modulation in underground channel using empirical values of coherence bandwidth, channel transfer function, and return loss of antenna. They used three different types of soil and under varying levels of soil moisture conditions.

WUC antennas are different from traditional antennas used for OTA communication because of deployment in soil. In 1909, Somerfeld's seminal work [223] laid the foundation of study of EM waves propagation. For the complete 20th century, EM wave propagation in subsurface stratified media and effect of medium on EM waves has been investigated thoroughly in many works [6, 7, 8, 13, 20, 28, 70, 72, 78, 79]. These studies uses infinitesimal dipole of unit electric moment for analysis of electromagnetic fields. However, it is desirable to use finite size antenna with already known field pattern, current distribution and impedance for practical purposes. Field calculations and dipole numerical evaluations for lossy half space was first studied in [134]. In [78], authors extensively analyze the propagation of EM wave along the interface. However, this work does not apply to underground buried antenna. Buried dipole were analyzed in lossy half space in [28]. The authors presented the ground wave attenuation factor of far-field radiation from UG dipole and depth attenuation factor using two vector potentials. However, it does not consider the current reflected from the soil-air interface. In [7], authors calculate the field component per unit dipole using Hertz potential. The difference between the study in [28] and [7] is that the former ignores the displacement current in lossy half space. Authors in [72] gives the Hertzman dipole in an infinite isotropic lossy medium. EM fields are improved by considering lateral waves and half-space interface in [20, 74].

Studies in [19, 19] analyze antennas in a matter where antennas EM fields have been theoretically derived in half space and infinite dissipative medium. These analysis assumes perfectly matched dipole antennas, hence, do not consider the return loss. Relative gain expressions of underground antennas are developed in [20, 79] without empirical results. The impedance of dipole antenna inside the solutions is evaluated in [22]. It discusses the effect of antenna depth, dipole length, and solution's permittivity. However, this work cannot be used in WUC because of difference between soil and solutions permittivity. Moreover, it does not consider change in permittivity occuring because of soil moisture. [24] studies the communication between the buried underground antenna without considering orientation and impedance of antenna. Another work [18] conduct the performance analysis of four antenna buried in refractory concrete. In this work, the transmitter is buried at 1m depth and author does not consider the concrete-air interface. [11] analyze circularly polarized patch antenna. It does not consider the interface effect and antenna is buried at 3cm depth in concrete.

Current WUC applications and experiments calculate the soil permittivity by using soil dielectric model [26, 54] which evaluates to actual wavelength used for the antenna design [74]. In [74], an WUC-based elliptical planar antenna is designed. It, using the same frequency, compares the antenna wavelength in soil and air to determine the size of the antenna. However, this methodology lacks in providing impedance match. [80] presents results from the experiments on Impulse Radio Ultra-Wide Band (IR-UWB) WUC without considering the effect of soil-air interface. [249] designs surface-based lateral wave antenna and does not considers the underground scenarios.

Impedance change in soil cause disturbance. This is similar to the disturbance caused by impedance change of hand-held device in close proximity with human body [32, 248] or that by devices which are implanted in the human bodies [38, 57]. Experiments results obtained from these applications shows that the human body contributes to performance degradation of antenna. Even these studies are similar, they still cannot be used in WUC because of the difference between the permittivity of soil and human bodies. Permittivity of human body is greater than the soil. Moreover, permittivity of human body is static whereas soil has varying permittivity mainly dependent upon the moisture. For example, at frequency of $900\,\mathrm{MHz}$, human body has permittivity of 50 [248] and that of soil with $5\,\%$ moisture is 5 [26].

Beamforming has been investigated for over-the-air wireless channel [4, 5, 11, 24, 27, 28, 79] and MI power transfer [21]. However, there exist no work in the literature on UG beamforming. Using beamforming, lateral components [19] in UG communications can go to the longer distance which is normally limited to $8\,\mathrm{m}$ - $12\,\mathrm{m}$ owing to high level of attenuation suffered because of soil [145].

There has been discussion on soil permittivity and soil moisture in the literature. Here some of those techniques are discussed for comparison purpose. This comparison will highlight the difference and similarities between different techniques. Some of the method used for quantifying water content in the soil includes: gravimetric method, GPR, TDR, capacitance probes, hygrometric techniques, tensionmetry, nuclear magnetic resonance, resistive sensors, gamma ray attenuation, electromagnetic induction, remote sensing, neutron thermalization, and optical methods.

Firstly, techniques which are used in laboratory for the soil properties estimations are discussed. laboratory based. Authors in [12] soil density, soil moisture and frequency to derive EM parameters of the soil. The model restricted soil moisture weight to $20\,\%$ and it need rigorous methods of sample preparation. Authors in [6] develops a probe-based lab equipment which uses vector network analyzer (VNA)in the frequency range of $45\,\mathrm{MHz}$ to $265\,\mathrm{MHz}$. In [74], a model for estimating a dielectric permittivity of soil is developed on the basis of empirical evaluation. Authors in [7] develops tyje model for dielectric permittivity for frequencies greater than $1.4\,\mathrm{MHz}$. Peplinski in [26] modify this model to work in the frequency range of $300\,\mathrm{MHz}$ - $1.3\,\mathrm{GHz}$. A detailed survey for soil permittivity estimations is given in [6]. All of these methods are performs in laboratories and requires soil sample from the site. Collecting soil sample from the soil is very labor intensive and do not represent he in-situ soil conditions. Therefore, it is required to developed automated techniques for monitoring the soil moisture.

Another approach of measuring soil properties is given in [25]. It is based on TDR and require refractive index and impedance of soil. [67] propose a technique to estimate of EM properties of soils for detecting Dense Non-Aqueous Phase Liquids (DNAPLs) hazardous materials using Cross-Well Radar (CWR). This technique transmits wideband pulse waveform in the range of $0.5\,\mathrm{GHz}$ to $1.5\,\mathrm{GHz}$. It also calculates soil permittivity with transmission and reflection simulations in dry sand. The well-explained survey on measurement of time domain permittivity in soils is presented in [70]. For TDR-based approaches, it is required to install sensors at each experiment location. However, in order to make effective decisions in agriculture, real-time soil moisture sensing is the primary requirement.

Many studies have been proposed to investigate antenna related soil properties. An attempt to measure electrical properties of earth using buried antenna has been proposed in [60], [61]. However, this method requires measuring the input reactance for obtaining electrical parameters of the material, and length of antenna is also required to be adjusted to get zero input reactance. [62] uses Fresnel reflection coefficients to estimate GPR-based soil permittivity with soil antenna. However, they do not provide empirical validation and also require a complex time-domain analysis. In [3], dielectric properties of soil are presented using wideband frequency domain and frequency range of 0.1 GHz - 1 GHz. It uses impedance measurement equipment (LCR meter) and VNA. In [24], [75], complex dielectric properties of soil are measured using frequency domain method which requires placing soil in the probe.

Soil moisture and permittivity can also be measured by using GPR method. [13] estimate ground permittivity by correlating ground dielectric properties with cross talk of early-time GPR signal. However, GPR method requires calibration and work only for shallow depths (0 – 20cm). Furthermore, soil moisture measuring technique cannot be limited to a certain burial depth.

Another important method of measuring soil moisture is remote sensing. Remote sensing has a high range of measurement [69] and is sensitive to soil water content [18]. There are two major type of remote sensing: active and passive. Passive remote sensing [20] has low spatial resolutions which can be improved by active remote sensing technologies, however, active methods limits the soil moisture readings to few centimeters of the topsoil which highly effect the readings taken [59]. Table 7.1 summarizes the existing work done in WUC.

1.4.1 Limitations of Over-the-Air Wireless in Soil

There are many research challenges face by the development and widespread of WUC. These challenges must properly be investigated. A centralized networking solution for WUC can be classified in to two architectures: (1) One with only buried UG nodes communicating with the AG node using UG links, and (2) Hybrid WUC employing both UG and AG nodes (static and mobile) to communicate through UG and OTA links [1, 70]. Apart from OTA links, UG2AG and AG2UG links are also being used extensively. Therefore, multi-hop networking involving UG2UG links must be investigated in detail.

A detailed analysis of UG2UG communication must be performed to address the WUC challenges. Although, all challenges cannot be solved owing to the challenging environment of WUC, however, identifying and proposing solutions for the major challenges is also an important contribution to it's development. To that end, the WUC research challenges are discussed below:

A. Antenna problem - A radio communication can be analyzed theoretically in two phases: (1) the antenna problem and (2) the propagation problem. WUC model is an underground propagation model. A dipole antenna with an ideal isotropic radiation pattern can guarantee high accuracy with combination of generic antenna gains and initial decays. However, with unavailability of ideal antennas, more practical approach would be to introduce specialized antenna factor for DW, RW, and LW to achieve

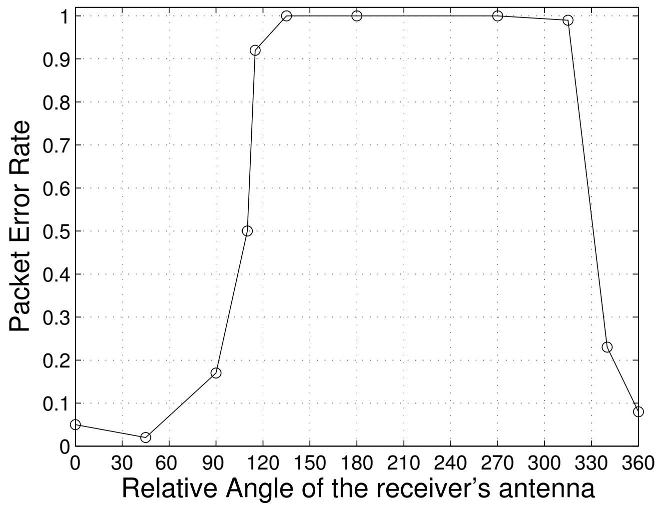

Fig. 1.5: Effects of the VWC on the ratio between antenna's length and wavelength of the signal [57]

more accuracy. Furthermore, conducting empirical investigations using large number of different values for burial depths, transmit power levels, and VWC, can precisely address the antenna problem.

Underground channel modeling with antenna problem is a very complex task. The complexity level increases manifolds even if one component of antenna problem is considered for modeling. To understand this issue, consider an example of the radiation pattern of the antenna and its implied directivity gain. Figs. 1.5 and 1.6 shows how VWC impacts the radiation pattern of an antenna. First, change in VWC changes the signal wavelength in soil which will also change the ratio between the signal's wavelength and antenna's fixed length ($17.3\,\mathrm{cm}$). The given values are from Mica2 mote (a 1/4 monopole antenna) antenna operating at $433\,\mathrm{MHz}$. The ratio $\frac{\text{length}}{\text{wavelength}}$ considers two times of Mica2 antenna length, e.g., $34.6\,\mathrm{cm}$, and half the wavelength of signal in soil or air. The two-fold increase in length is mandatory because a 1/4 monopole antenna is same as 1/2 dipole antenna with ground structure representing half of the antenna. Therefore, 1/2 ratio for a half-wave dipole is shown for the comparison. VWC causes decrease in wavelength which in turn increase the length-wavelength ratio.

Fig. 1.6 plots the elevation pattern of a linear dipole antenna (oriented vertically) with length measured in terms of wavelength [253]. The change in ratio ($\frac{\text{length}}{\text{wavelength}}$) (Fig. 1.5) is represented using different radiation pattern (Fig. 1.6). VWC causes increase in ratio making the radiation pattern behaviour monotonous.

The antenna problem differs with type of antenna and orientation of antenna and should be addressed accordingly for each antenna scheme. However, all antenna schemes

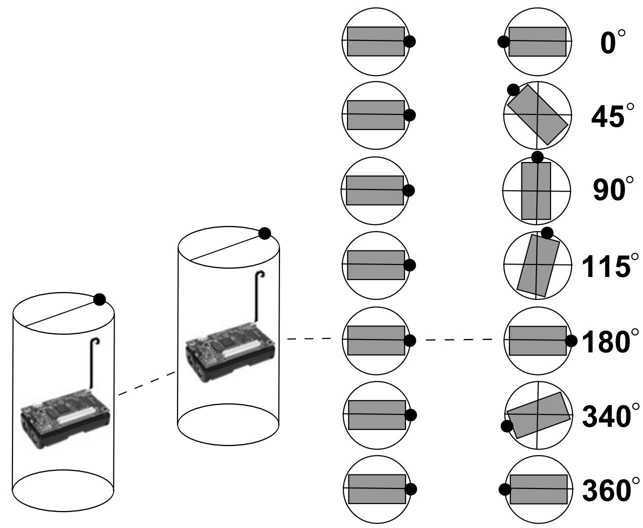

Fig. 1.6: Volumetric Water Content effecting radiation pattern monopole antenna [57]

are not suitable for underground communications. Therefore, it is recommended to identify antenna schemes which can improve the performance of UG2UG, UG2AG, and AG2UG links to support WUC channel model with adding more antenna models. A possible solution is suggested along with th results in [23, 60, 68, 70, 77, 257]. It uses an ultra-wide band antenna for UG2AG and AG2UG links and traveling-wave antenna to study lateral wave propagation in UG2UG links. An empirical investigation must be done to evaluate the solutions for different depth and transmit power level.

B. Burial depth - In WUC model, burial depth can be defined as the distance between antenna center and soil surface. The existing results shows a strong correlation between depth and communication performance. Hence, burial depth of sensors and radio modules has no effect on the model but antenna's depth does. Adjusting to optimal depth can significantly extend the communication range along-with a high power transceiver. There are also some design constraints in WUC which cannot be violated, e.g., in crop irrigation, nodes must be below the topsoil region where plowing happens. The challenge is to deploy antenna in topsoil such that they are not affected by the mechanical activities in their vicinity. One solution is installing and removing nodes during such activities, however, it will increase the deployment cost. Apart from the increased cost, installation and calibration of soil sensors is also a time taking process. In some scenarios, where sensor(s) and processors are permanently fixed in subsoil, easy installation/removal is only possible for communication module near to soil surface (see Fig. 1.7). In such cases, sensors are fixed and only removable component is the long-range communication module. This module requires a short-range transceiver (with deeply buried sensor nodes) and a transceiver which enables communication

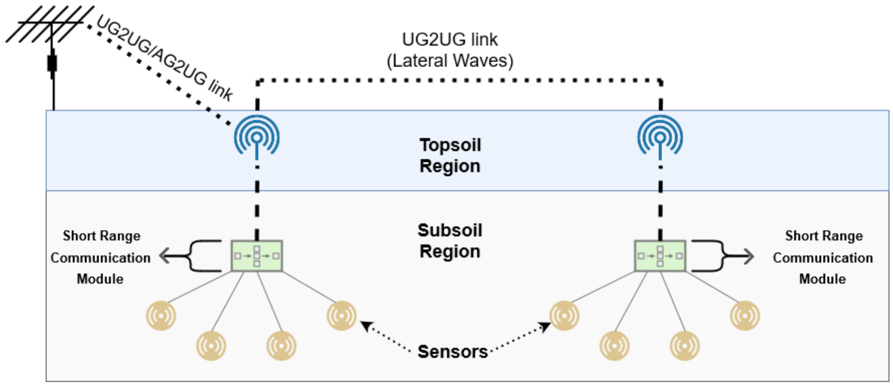

Fig. 1.7: The WUC deployment

between above-ground devices and other long-range modules. There is a need to investigate optimal values of burial depth (including d_{bg}=0) for such long-range module.

C. Housing for the sensor nodes - In some WUC, concealment of sensor nodes is more important than the high depths. One solution is to use plastic boxes which can conceal processor, communication module and antennas. However, it has never been investigated in detail for UG2UG communication and preliminary experiments shows completely different effects on communication performance. A scenario using stratified media (air/soil) must also be analyzed for UG2UG links in WUC.

D. Direct and Reflected waves. So far, communication through lateral waves has been presented as a power-efficient solution to achieve a long range UG2UG communication. WUC model can be converted into a simple LW model. However, it is not recommended to do so, because the short range communication is mainly based on DW (Fig.1.7). Some components of WUC model can also be used in development of UG2AG/AG2UG channel models. Inter-node distance can be increased using directional antennas and high-power transceiver.

E. Lateral waves. There is a need of detailed empirical and theoretical evaluation of lateral wave propagation for UG2UG links in WUC. The results discussed are highly limited by the power-efficient transceiver and antennas. Special antennas and high-power transceivers must be used to achieve long-range communication. It will contribute towards complete validation of WUC model.
Effect of using terminated traveling-wave antennas needs to be studied. These antennas were used for underground communication previously [23, 77, 257]. Therefore, these studies can be re-investigated for a typical WUC scenario with modified deployment parameters. The power requirements of multi-hop LW/UG2UG technique and centralized one-hop UG2AG/AG2UG must be studied in detail to give extremely important power related guideline for developing WUC.

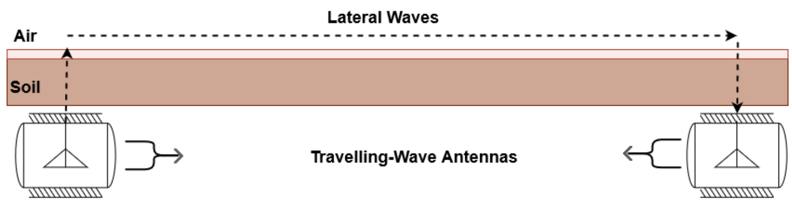

Fig. 1.8: Lateral waves can potentially be applied in security applications for WUC

It is also important to study the impact of snow, water and obstacles in surface on UG2UG links communicating using lateral waves. The results from such studies can further complement WUC model. These studies can be used for security purposes, e.g., detecting intruder in border patrol application. The detection process uses the disturbance of wireless channel (Fig. 1.8).

F. UG2AG and AG2UG channel models. A detailed channel model for UG2AG and AG2UG links must be developed. There exists no generic model which can be applied to all WUC. There are some preliminary empirical investigation done by [60, 70], however, an in-depth theoretical analysis is still needed. Overall energy consumption requirement for such solution also needs to be investigated. Lateral wave propagation already has its application in UG2UG links. However, a comparative study for the power budgets of multi-hop LW/UG2UG approaches and centralized one-hop UG2AG/AG2UG should be done.

1.5 Anatomy of a WUC Module

The underground nodes currently used in WUC testbeds suffer from several shortcomings. These shortcomings lead to reduced communications performance in WUC, reduced experimental effectiveness, and higher costs. To address these faults, there is need of nodes tailored to WUC. The following capabilities are desirable in these nodes [65], [210]:

Environmental Factors - The current generation of WUC nodes is designed to support academic research being conducted primarily in a laboratory setting. Hence, the experiments do not consider many feature of uncontrolled outdoor environments. First, the WUC nodes cannot be reprogrammed without interfacing to a special hardware board. If the devices are to be reprogrammed in the field, they must either be dug up, or each mote should be deployed with an additional hardware programming board. Digging up the WUC nodes is a time-consuming and a difficult process. Deploying the additional hardware to reprogram the WUC nodes underground is expensive, and complicate the deployment process [65, 210].
Secondly, remote charging of the nodes is not possible. If a node's battery ends during an experiment, a buried node must be dug up for the battery replacement. It is an

extremely time consuming operation, and the performance of an experiment may be suboptimal until the node is replaced [38, 43].

Propagation - While the current experiments demonstrate the viability of WUC, the performance could be further enhanced by tailoring the radio of the mote as per the requirement of the underground networks. The radios of the current WUC nodes are designed to communicate over-the-air. The parameters of the radios are not well matched to the WUC environment in terms of transmit powers and frequencies. The existing WUC nodes can be modified to better match the desired parameters, however, it is not as effective as choosing a radio specifically matched to the needs of a WUC node [36].

Sensing - The sensor packages that can be deployed with the current generation of WUC nodes do not collect all the information desired for an underground environment, or contain many extra sensors that are not useful for WUC. These added sensors increase the cost of deploying experimental testbeds.

All of these areas can be improved by using a node designed specifically for WUC. To address these challenges, a WUC node should be designed to operate on a limited power reserves, monitor the underground environment, and communicate the results to aboveground nodes. The design of the different desirable aspects of a WUC node are give below [65, 210].

(i) **Transmitter/Receiver -** A radio should have a high transmit power and be able to operate on a variety of sub-1 GHz frequencies that are suitable for WUC [34]. The radio implementation can be modified to meet the specific requirements of the antennas and RF environment of WUC-application. It will increase the transmission range and capabilities of a radio device.

(ii) **Microcontroller -** The microcontroller should be able to provide enough processing power [51]. One such example of a microcontroller is MSP430 which is extremely energy efficient and also extends the lifetime of the deployed sensors. The MSP430 can also interface to a variety of sensors, communication, and storage devices.

(iii) **Sensors -** The WUC node should contain a built in accelerometer and temperature probe with an ability of interfacing with an external soil moisture sensor. The combination of multiple sensors enables a node to accurately measure the characteristics of the underground environment. These measurements can help the radio to adapt to its environment in real-time. Accordingly, the sensor readings can be used to assess the viability of energy harvesting through kinetic vibrations [47].

(iv) **Data Repository -** WUC nodes should have an on-board micro-SD card for storage. This large storage space can be used to store extensive sensor readings for a long-term monitoring of the underground environment. By adding a large storage capability, the system can sense at a much higher rate than it can transmit information. After an extended deployment, the information from nodes can be recovered, and a highly detailed model of an underground environment can be developed from the stored sensor readings [52].

(v) Energy - WUC node should support a variety of energy sources with energy harvesting and external power transfer support that enables the system to sense at higher rates and operate for longer periods of time than the current generation of WUC nodes [65, 210]. Moreover, the nodes should also support recharging through a USB cable accessible from aboveground after the node has been deployed. Accordingly, the device can be recharged quickly in the field without removing and re-deploying a node in the testbed. The mote can also be enhanced with kinetic energy harvesting capabilities that will further increase the lifetime of the WUC nodes.

1.6 Research Challenges

The development in WUC has extended the research possibilities and brought some research challenges as well. Therefore, this section presents the research challenges in this area. Moreover, Table 1.3 shows the importance of these challenges in the different WUC applications.

Deployment
Deployment is a major issue in WUC applications because of the harsh underground environment [87]. The underground smart objects can easily be damaged by the aboveground activities, i.e., digging, plowing, harvesting. Therefore, node deployment is very difficult in WUC as compared to the terrestrial networks. The objects with high energy requirement should be deployed near to the surface so that frequent battery replacement can be done easily. High capacity batteries and power saving protocols can also be used to meet the requirement of high energy nodes. The deployment challenge become relatively severe in WUC applications such as seismic and Oil & gas exploration because of higher depth. Therefore, in [166], a MI-based WUC is used with managed and organized orientation of coils to minimize the power reflection. [95] reduces the complexity by using different deployment strategies (horizontal and vertical). One important issue to consider is the path loss occurring due to heterogeneous nature of soil. Unfortunately, there is a very limited work on efficient WUC deployment which aims to solve this challenge along-with the consideration of different operational parameters [33, 53, 55].

Channel Modeling
The EM signal attenuation is much higher in soil as compared to the terrestrial networks [44]. The major factors contributing to high attenuation loss is the soil permittivity and conductivity which was also the reason for inception of the MI-based WUC. Each layer of the heterogeneous soil effects the magnetic field differently. Given this behavior, [265] assigns a scaling factor to different depths. In [100], the authors studies propagation though the soil by calculating the skin depth of each layer. [229] characterizes the path loss for MI-based communication. [61] investigates the

Table 1.3: Research challenges for IOUT applications [114]

Research Challenge	Agriculture	Seismic exploration	Oil & Gas
Deployment	Medium	High	High
Channel modeling	Medium	Medium	High
Transmission range	Low	High	Medium
Latency	Low	Low	Medium
Reliability	Low	Medium	High
Security	Medium	High	High
Scalability	Low	Medium	Medium
Robustness	Low	Medium	High
Networking	High	Medium	Medium
Cloud computing	High	Medium	Low
Fog computing	Low	Medium	High
Localization	Medium	High	Medium

asymmetric transceiver to cope up with the case of coils misalignment in MI-based WUC. Path loss has been extensively studied for each type of the wireless channel, however, few efforts have been made for WUC systems. Therefore, this area of WUC needs special consideration.

Transmission Range

MI-based WUC with all its advantages, i.e., not effected by boundary effects & multipath fading [169], has a disadvantage of limited transmission range. This is because of high path loss in the soil. In [92, 166], authors proposed using relay coils to extend the transmission range. Similarly, [92, 104] proposed using super conductors and meta-materials for this purpose. Large coils were used in [97] with an aim of achieving high transmission range, however, it might not be a practical solution. Therefore, achieving the long communication range for buried nodes is an important research issue.

Latency and Reliable Communication

Latency and reliable communication is the primary requirement of all critical applications such as Oil & Gas exploration. Late or incorrect sensors reading can cause major disaster. WUC challenging environment is the major hindrance in achieving the reliable communication. Although, the reduced latency and reliability is one of the major requirement of the conventional IoT as well [47, 51], however, in WUC, this issue needs more deliberation due to tough operating parameters and regulations on sub-surface environment. It is not possible to meet the WUC communication requirement with any single system. For example, wired communication provides reliability and low latency whereas wireless solutions are scalable with low complex. Therefore, it is important to develop a WUC with low latency, lower transmission delays and minimized sensor failures.

Security
Security is the least studied aspect of WUC systems. WUC security includes: security of equipment, and security of communication protocols. Node replication, jamming the signal, and worm hole are few potential security attacks that can occur in WUC systems. A security breach can be used to raise false alarms. Responding to the frequent false alarms can exhaust network resources. In [154], authors discusses the security issues (e.g., forward and backward security) and malicious attacks (e.g., node compromise attack) on a cloud-based IoT. Authors in [47] uses the data tagging technique for improved data security. They uses information flow control (IFC) for this purpose. A secure IoT architecture using host identity protocol (HIP) and datagram transport layer security (DTLS) is presented in [53]. [204] provides an extensive security survey in IoT. These studies are targeted towards improving security in terrestrial networks, however, these can be modified to WUC environment by introducing underground operational constraints. For example, old Oil & Gas systems are being transformed to digital WUC systems. Therefore, it is required to update security of such globally connected systems which, otherwise, in an event of cyber attack, can lead to some disastrous situation. Blockchain technology can be also be used in WUC systems to deal with the cyber crimes [49, 54].

Scalability
Scalability issues can rise due to the factors such as: higher network density, high energy-consumption of underground things, node failures, routing overhead, low memory of underground nodes, and vendor-specific nodes can cause interoperability issues. [55] uses spatio-temporal stochastic modeling to deal with the scalability in WUC. For tunnels, [107] proposed an adaptive structure-aware WUC system. Interoperability issue is discussed in [107] using middleware protocol. Heterogeneity of sensor nodes is studied in [259]. The mentioned work deals with the scalability of terrestrial IoT, however, these can be modified as per requirements of WUC systems. For example, high path loss in soil limits the deployment of large wireless network. This problem is studied in [26, 250] which uses the sink nodes to connect with the sparsely buried sensor nodes. It uses the energy harvesting to increase the lifetime of the nodes. Besides these solutions, it is important to efficiently develop a self-healing and self-organizing WUC systems which can overcome the scalability issues.

Robustness
An underground channel is very unpredictable facing the issues like: energy constraints,

dynamic topology, sparsity of nodes. Hence, achieving robustness is very critical in WUC systems. A small world model is proposed in [113] for the improvement of latency and robustness by considering the local importance of smart objects. Extensive literature exist for the improvement of robustness in terrestrial network [35], however, work in robustness in WUC is limited to the mining application. For example, [85] improve the robustness of an underground mining by using a wireless mesh network. One of the major challenge in the WUC systems is to develop robust communication and data gathering techniques. Communication range of EM waves in soil is highly limited because of attenuation. However, magnetic induction is considered relative robust for communicating in the soil but requires perfect orientation of the coils. The research of MI-based WUC for robustness is still not mature and needs to be studied further.

Hybrid Sensing

Hybrid sensing systems includes the usage of multiple sensor systems and integration of their signals, e.g., long-term underground fiber sensors can be combined with short-term ground penetrating radars fro the purpose of detection and localization. SoilNet Systems [7] is an hybrid sensor system which combines Zigbee network with wired communication. Zigbee network is used for above-ground nodes and wired communication is used fro the underground nodes. A combination of EM- and MI-based can be used for providing long-range downlink (EM-based) and short-range uplink (MI-based) communication [97]. Therefore, hybrid sensing systems can improve the efficiency of WUC systems.

Software Defined Networking (SDN)

Software Defined Networking (SDN) provides robustness, scalability, reliability and secure networking solution for WUC systems. It is different form conventional networking solutions in that it separates the control logic from the networking hardware. These advantages make its suitable for the usage in underwater environment. A surface station can be any SDN controller which communicates with the underwater sensors through in/out-band control channels [13]. The SDN controller will separate the data plane and controller plane. Such technique can also be used for WUC systems [148]. SDN-based WUC will have lower network complexity, improved congestion control mechanism, increased network life, efficient utilization of network resources, and reduced latency. For example, SDN-based WUC for Oil & Gas can allow users to efficiently manage the system by providing the global view of buried sensors nodes. SDN-based WUC can also be used in agricultural applications for achieving a scalable network solutions. Furthermore, data visualization can be used with SDN-controller for correlation of sensor data. These advantages of SDN paradigm forces researcher to look into the possibilities of SDN-based WUC systems [29].

Big Data

Massive amount of data is generated by WUC applications (agriculture, seismic surveying, and oil/gas fields). This data should properly organized, correlated and analyzed for making accurate decisions [65]. Integration of big data and traditional IoT is already being studied extensively, e.g., [19] presents the application of big data in IoT. In [143], authors studies the application fo context-aware computing in IoT. These works motivate and presents an opportunity fo integrating big data analytics with WUC system. For example, Oil & Gas WUC generates glut of data and managing that data is the major concern of respective industries [40, 41]. Similarly, geo-scientists spends major portion of their time (nearly 50 %) on managing data. Big data provides an opportunity to handle such big amount of data and perform analysis. Therefore, proper data analytics tools must be developed for the WUC systems.

Fog and Cloud Computing
Cloud/fog computing provides different feature (scalability, mobility, low delays, and location awareness) for an efficient WUC systems. Cloud computing has been used for the management purposes in Oil & Gas industries whereas fog computing has been used for reducing data traffic and analysis of data at edge [144]. In Oil & Gas industries, huge data generated by the upstream operations (e.g., drilling and seismic exploration) is a major challenge. Fog computing can be used for provision of localized data analytic being generated in real-time. It helps in minimizing communication delays and faster event response. Moreover, time-critical applications require efficient decision making procedure because it is possible that decision making opportunity is gone by the time data reaches the cloud. Hence, fog computing should be integrated with WUC systems [44].

Efficient Localization Methods
Localization can be done in many applications such as WUC monitoring, geo-tagged sensing, and optimized fracturing. There are limited studies which tries to find location of buried nodes of MI-based WUC. In [120], authors developed a testbed for tracking objects in MI-based WUC. [5] studies how mineral and rocks in underground environment effect the accuracy of localization. The accuracy of MI-based WUC is also investigated in [37, 42, 156]. It is important to note that localization work exist only for the MI-based and there is no such investigation done in EM-, acoustic-, and VLC-based WUC. Therefore, robust and accurate localization methods are required for these WUC systems.

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